# Design of the ST 3 Formation Flying Interferometer

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**Abstract.** The Space Technology 3 mission (formerly Deep Space 3), scheduled for launch in 2003, will be the first long baseline optical interferometer in space. The interferometer will operate in both a single spacecraft mode and a formation flying mode using two spacecraft with a separation of up to 1 km. The primary goal is to validate interferometer and formation flying technology for future missions, but ST3 is also designed to return scientific data within its cost and mission constraints.

This paper presents an overview of the current design, highlighting some of the technical challenges that must be overcome.

## 1. Introduction

The Space Technology 3 mission, now part of NASA's Origins program, is currently scheduled for launch in 2003. The primary goal is to demonstrate a separated spacecraft optical interferometer. The technologies of formation flying and space-based optical interferometry are vital ingredients for future missions such as the Terrestrial Planet Finder (Lawson, this volume). ST3 will measure fringe visibility amplitudes; it has no astrometric or imaging capability. The performance goals are summarized in Table 1, and the science goals of the mission are described elsewhere in this volume (Linfield & Gorham 1999).

The current design is based on 2 spacecraft, termed the combiner and the collector. These will be launched together into an Earth trailing orbit, by a Delta II 7325 rocket. The nominal 6 month mission duration has the following stages: (i) 3 weeks of formation flying experiments (no interferometry); (ii) 3

Table 1. ST3 performance goals

| | |
|---|---|
| Wavelength | 450 - 1000 nm |
| Spectral channels | 80 |
| Baseline | 40 - 200 m |
| Spacecraft separation | 50 - 1010 m |
| Visible magnitude | $2 < m_V < 8$ |
| Minimum source visibility for $m_V = 8$ | 0.3 |
| Calibrated visibility accuracy, each channel | 0.02 |

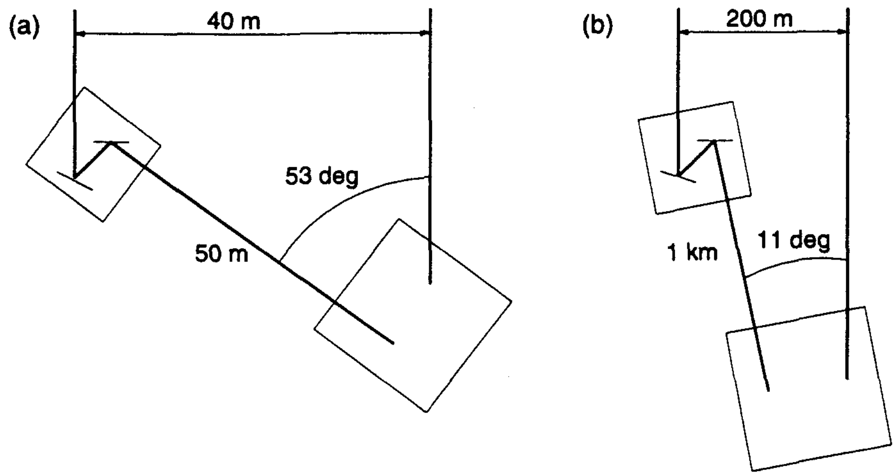


Figure 1. Schematic observing geometry for ST3 (not to scale). (a) Shortest baseline. (b) Longest baseline.

weeks of combiner-only operation (the instrument is operated as a monolithic interferometer with a fixed baseline of ~1 m); (iii) 4.5 months of formation-flying interferometry. This paper describes only this last stage.

Figure 1 shows the basic observing geometry for the separated spacecraft interferometer, at both the shortest (40 m) and longest (200 m) baselines. The delay offset is 20 m in each case (and for all intermediate baseline configurations), compensated by a fixed 20 m delay carried on the combiner. This unique geometry, and the optical layout for ST3, are discussed further by Gorham et al. (this volume). In the description that follows, 'left' and 'right' are used to label the two starlight paths according to the view shown in Fig. 1, i.e. the collector is part of the left starlight path.

The next section steps through the sequence that converts 2 free-floating spacecraft into an interferometer capable of measuring fringe visibilities. The various sensors and actuators required for this process are also described.

## 2. Acquisition Sequence

The visibility of a target star is measured at multiple baselines and orientations, and unresolved objects must be observed at regular intervals for correct calibration of the instrument. The steps below are repeated for each $(u, v)$ point.

The steps in the sequence are: (1) Move Spacecraft, (2) Acquire Right Starlight, (3) Acquire Angular Metrology, (4) Acquire Linear Metrology, (5) Acquire Left Starlight, (6) Measure Delay and Delay Rate, (7) Cool Formation, (8) Find Fringe, (9) Track Fringe, (10) Measure Fringe. Steps (2) through (7) are illustrated schematically in Fig. 2.

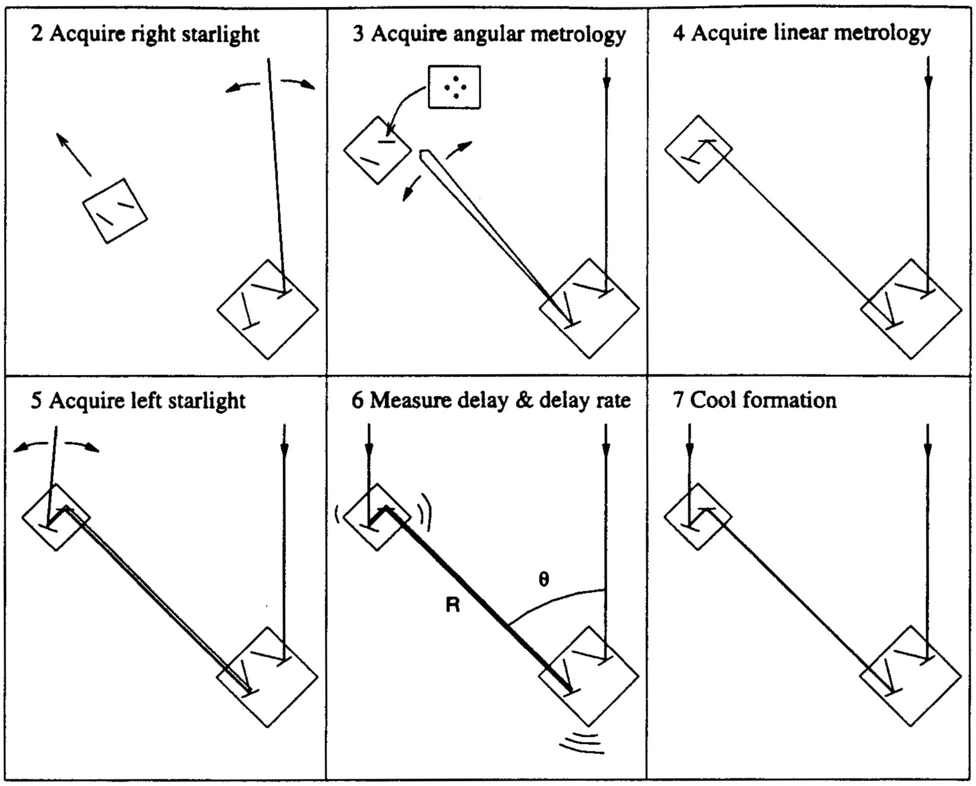


Figure 2. Steps in the ST3 acquisition sequence. The target star lies in the vertical direction.

### 2.1. Move Spacecraft

The required vector between the two spacecraft in inertial space is determined from the desired baseline and direction to the target star. Star-trackers on each spacecraft provide attitude information (~10 arcsec accuracy), and the vector to the collector with respect to the combiner's coordinate frame is measured by the Autonomous Formation Flying (AFF) sensor. The AFF sensor uses a carrier frequency of 32 GHz, modulated with codes based on the Global Positioning System. Two transmit and four receive antennas per spacecraft give coverage over $4\pi$ steradians. The range accuracy is ~1 cm; bearing angle is measured to ~3 arcmin.

The spacecraft will require fine thrusters (e.g. cold gas or pulse plasma thrusters) for attitude and positioning adjustments. With at least 6 on each spacecraft, different pairs can be fired for full translational and rotational control. Reaction wheels may be considered for fine attitude control if the generated vibrations are sufficiently small.

## 2.2. Acquire Right Starlight

Once the combiner is stabilized at the desired position and attitude (the collector can still be moving), the right combiner siderostat (12 cm diameter) is rotated to the required position (a function of the baseline length – see Fig. 1) and the target star is acquired in the right starlight pointing field of view ($\sim \pm 2.5$ arcmin). The star is centered and a pointing control loop is closed, using a 2-axis fine gimbal on the siderostat to track out small pointing changes.

## 2.3. Acquire Angular Metrology

An infrared (1320 nm) metrology laser is injected at the combiner optics out along the left starlight boresight. At the center of the transfer flat on the collector is an Intensity Gradient Detector (IGD); the basic design consists of 4 infrared photodiodes equally spaced around the circumference of a circle. When the photocurrents are all equal, the metrology beam is centered on the transfer flat. The metrology beam is steered by the left combiner siderostat; a search pattern is executed until the laser is detected at the IGD. A pointing loop is then closed around the IGD and the left combiner siderostat. The angle $\theta$ (Figure 2) is now given by the difference between the encoders on the left and right siderostats, with an accuracy of $\sim$1 arcsec. The differential precision is $\sim$100 mas.

## 2.4. Acquire Linear Metrology

At the center of the collector siderostat is a corner cube retro-reflector which returns the metrology beam to the combiner. The beam is part of a heterodyne metrology gauge that measures path length changes to $\sim$5 nm. Additional metrology gauges are needed to monitor path length changes within the left side (including the variable delay line) and right side (including the 20 m fixed delay line) of the combiner optics. The two gauges on the left side will be implemented together with a single beam and two retro-reflectors, using phase modulation to discriminate between the two return signals.

## 2.5. Acquire Left Starlight

With the angular metrology pointing loop closed, the left starlight boresight passes through the center of the collector optics. Acquiring the star on the left pointing field of view (both left and right starlight pointing are handled by the same CCD camera on the combiner) requires that the collector siderostat is set to the correct angle (which depends on the baseline length – Fig. 1) and the collector spacecraft has the correct attitude. The left pointing field of view is limited by a field stop to $\sim \pm 1$ arcmin; this is to minimize the impact of stray light due to sunlight reflected off the collector. The star is centered at the desired position by closing a third pointing loop around the pointing camera and the collector siderostat.

## 2.6. Measure Delay and Delay Rate

With all 3 pointing loops closed, the formation geometry is sensed by: the star-trackers on each spacecraft ($\sim$10 arcsec); the encoders on the 3 siderostats ($\sim$1 arcsec); the range measurement from the AFF ($\sim$1 cm); and the range rate from the laser metrology system. Before the Find Fringe process starts, it is necessary to estimate the delay and delay rate. The uncertainties in these values will define the scope of the fringe search; the current design requires 5 mm delay and 3 $\mu$m s$^{-1}$ delay rate knowledge (both $1\sigma$). The delay (optical path difference, OPD) is given by

$$X = R(1 - \cos\theta) + D_{\text{var}} - D_{\text{fix}} + F_1(\text{Combiner att.}) + F_2(\text{Collector att.}), \quad (1)$$

where $R$ is the range of the collector from the combiner, $D_{\text{var}}$ comes from the variable delay line, $D_{\text{fix}}$ is the fixed internal offset (including the 20 m fixed delay line), and $F_1$ and $F_2$ are functions of the spacecraft attitudes. Through differentiation, it is easily shown that the largest delay uncertainty (5 mm) arises from the AFF range measurement on the shortest baseline (where $\theta = 53°$).

Delay rate estimation uses the linear metrology instead of the AFF, and the limiting factor is then the precision with which small changes in $\theta$ can be measured at $R = 1$ km. The goal of 3 $\mu$m s$^{-1}$ is equivalent to the collector moving in the transverse direction by 1.5 mm (0.3 arcsec) in 100 s.

## 2.7. Cool Formation

At this point the residual velocities of the spacecraft will give a much higher delay rate than the goal of 3 $\mu$m s$^{-1}$; the relative motion must be reduced to the required value before the fringe search begins. This is an iterative process in which the delay rate is measured, thrusters are fired to reduce the motion, the delay rate is measured again, and so on, until the formation has been 'cooled' to the necessary level.

In the cooled state, each of the 9 formation degrees of freedom (3 attitude per spacecraft, 3 dimensional vector separating spacecraft) has a deadband range through which the formation is allowed to drift. When the edge of a deadband is reached, small thruster firings reverse the direction of the drift. In addition to the delay rate requirement, it is desirable that there are no thruster firings during the fringe search; the deadbands must be large enough to accommodate this, which in turn sets a requirement on the articulation ranges of the fine steering siderostat gimbals. The spacecraft are also continually accelerated by solar radiation pressure, both in translation and rotation, requiring careful design to minimize these effects.

## 2.8. Find Fringe

A delay uncertainty of 5 mm ($1\sigma$) is much larger than for typical ground-based instruments. A delay search range of 20 mm ($\pm 2\sigma$) is needed to have a good chance of finding the fringe. The search strategy is simple, consisting of a sweep at constant rate from one end of the range to the other. Candidate detections that exceed a given threshold will be checked again for confirmation. The 4 bin method (Colavita 1985) operating on the output of an Avalanche Photodiode (APD) detector is currently baselined. This algorithm is relatively inefficient in this situation: a 20 mm search in under 1000 s requires a star of visible magnitude 6 or brighter.

An algorithm that operates on the dispersed fringe is much more efficient for ST3 (which has no atmospheric turbulence to deal with). Such an algorithm, which searches in both delay and delay rate, can complete the 20 mm search in 300 s for a magnitude 8 star. This algorithm is currently under evaluation.

### 2.9. Track Fringe

Once the fringe is found, a fringe tracking servo takes over. The delay line is dithered back and forth by one wavelength and the output of the APD is demodulated to give a visibility amplitude and phase using the 4 bin algorithm. Any drifts in the zero OPD position (e.g. due to spacecraft motion within the deadbands) are compensated by the variable delay line. For a magnitude 8 star, the fringe tracking bandwidth is estimated to be 0.4 Hz.

### 2.10. Measure Fringe

While one output of the beam combiner is used to stabilize and track the fringe, the other output is dispersed by a prism onto one row of an $80 \times 80$ CCD camera, providing 80 channels of spectral information spanning 450 to 1000 nm. The goal is to measure the stellar visibility in each channel with a precision of 0.01 ($1\sigma$).

One option is to read out the CCD row multiple times per cycle of the delay line dither. This incurs a large read noise penalty, however. A preferable scheme is to accumulate photons in each channel for a given fraction of the dither cycle, shift the charges in the active row of the CCD to the next row up, accumulate the photons in the now empty active row for the next fraction of the dither cycle, and so on. Each part of the dither cycle has a corresponding row of charge on the CCD which can be added to repeatedly over a long period of time before reading out the CCD. For an 8th magnitude star, a readout interval of ~60 s ensures that read noise has minimal impact on the sensitivity. Approximately 1000 s of total integration time will be needed to achieve a visibility precision of 0.01 in each channel for an 8th magnitude star.

## 3. Summary

The success of the ST3 mission depends on a number of systems – formation flying, laser metrology, actuated optics, detectors, control software, etc. – operating together at a large distance from the Earth. Many challenges will have to be overcome, and the lessons learned will be vital for future missions such as the Terrestrial Planet Finder.

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